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TITLE: DENTAL MATERIALS BASED
ON METAL OXIDE
CLUSTERS

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Dental materials based on metal oxide clusters

The invention relates to dental materials based on polymerizable metal oxide clusters.

Polymerizable compositions are known which, in addition to organic monomers, also contain polymerizable metal compounds.

US 2,502,411 discloses compositions which, in addition to unsaturated polymerizable organic compounds, contain a zirconium acrylate which is obtainable by reacting a water-soluble zirconium salt with a salt of (meth)acrylic acid. The zirconium compound is said to improve the wettability of ceramics, metals and cellulose. Details of the structure of the zirconium acrylates are not given.

DE 31 37 840 C2 discloses crystalline zirconium methacrylate of the general formula $Zr_4(MAS)_{10}O_2X_2(H_2O)_{2-4}$ in which MAS is the anion of methacrylic acid and X an anion from the group hydroxide, alkoxide, halide and carboxylate. The compounds are said to be suitable as cross-linking agents in the preparation of vinyl polymers by radical polymerization of vinyl monomers.

Schubert et al., Chem. Mater 4 (1992) 291 describe the preparation and characterization of methacrylate-modified titanium and zirconium alkoxides which are obtainable by reaction of the corresponding metal alcoholates with

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methacrylic acid, and Kickelbick and Schubert, Chem. Ber./Recueil 130 (1997) 473, of crystalline oxozirconium methacrylate clusters of the formulae $Zr_6(OH)_4O_4(OMc)_{12}$ and $Zr_4O_2(OMc)_{12}$ in which OMc is the anion of methacrylic acid.

DE 41 33 494 C2 discloses dental resin compositions based on polymerizable polysiloxanes which are prepared by hydrolytic condensation of one or more silanes of which at least one is substituted by a 1,4,6-trioxaspiro-[4,4]-nonane radical or an ethylenically unsaturated group.

Hydrolyzable and polymerizable silanes are known from DE 44 16 857 C1 which contain one linear or branched organic radical with at least one C=C double bond and 4 to 50 carbon atoms.

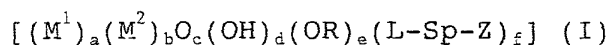
EP 1 022 012 A2 and US 6,096,903 disclose dental materials based on polymerizable and hydrolyzable methacrylate-modified or oxetane-group-containing silanes.

Silanes of the type described above can be condensed alone or together with another hydrolytically condensable compounds to form inorganic networks, which can then be cured via the C=C double bonds contained in the silanes by ionic or radical polymerization accompanied by the formation of inorganic-organic networks.

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The object of the invention is to provide dental materials with improved mechanical properties.

This object is achieved by dental materials which contain at least one cluster according to the general formula (I)



in which

- M^1, M^2 independently of each other, stand for a metal atom of the IIIrd or Vth main groups or the Ist to VIIIth sub-groups of the periodic table;
- R is an alkyl group with 1 to 6 carbon atoms;
- L is a coordinating group with 2 to 6 complexing centres;
- Sp is a spacer group or is absent;
- Z is a polymerizable group;
- a is a number from 1 to 20;
- b is a number from 0 to 10;
- c is a number from 1 to 30;
- d, e independently of each other, are in each case a number from 0 to 30;
- f is a number from 2 to 30.

The respective values of the indices a to f can vary according to the type, number and valency of the metals and ligands. The indices c, d, e and f preferably assume such

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values that the positive charges of the metals M^1 and M^2 are completely equalized and the cluster is neutral. The cluster can however also be positively or negatively charged. In this case, the charge of the cluster is compensated by suitable counterions such as for example H^+ , alkali or alkaline-earth metal ions, NH_4^+ , NR_4^+ with R^0 = alkyl, in particular C_1 to C_4 alkyl, or OH^- , $R'-COO^-$ with R' = alkyl, preferably C_1 to C_{10} alkyl, particularly preferably C_1 to C_4 alkyl, or halide, preferably F^- or Cl^- . The clusters (I) have for example a charge of -4 to $+4$, in particular $+1$ to $+4$.

The group L can be chelating or bridging, i.e. the complexing centres of the group L can be connected to the same metal atom or preferably with two or more different metal atoms.

The ligand (L-Sp-Z) can be neutral or have a negative charge. Neutral ligands or ligands with a single to triple negative charge are preferred.

The ligands (L-Sp-Z) present in the cluster can be the same or different. Clusters which contain 1 to 4, preferably 1 or 2 kinds of ligands (L-Sp-Z) are preferred. For example, two methacrylate ligands can be replaced by allyl acetoacetate in the cluster $Zr_4O_2(\text{methacrylate})_{12}$. The resulting cluster has the formula $Zr_4O_2(\text{methacrylate})_{12}(\text{allyl acetoacetate})_2$, both methacrylate and allyl acetoacetate

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being ligands of the type (L-Sp-Z), i.e. the cluster contains two kinds of ligands of the type (L-Sp-Z).

Clusters which contain only a small proportion of alkoxy groups ($d > e$) are preferred. Preferably $e \leq (a+b)$, particularly preferably $e = 0$.

Preferred definitions, which can be selected independently of each other, for the individual variables are:

- M^1, M^2 = independently of each other, Ti and/or Zr;
- R = an alkyl group with 1 to 4 carbon atoms, in particular 1 to 2 carbon atoms;
- L = α -hydroxycarboxylate ($-\text{CH}(\text{OH})-\text{COO}^-$), α -aminocarboxylate ($-\text{CH}(\text{NH}_2)-\text{COO}^-$), β -diketonate ($[-\text{C}(\text{O}^-)=\text{CH}-\text{C}(=\text{O})\text{R}^k]$; with R^k = alkyl, preferably C_1 to C_6 alkyl, particularly preferably C_1 to C_3 alkyl, in particular methyl, sulfonate ($-\text{SO}_3^-$) or phosphonate ($-\text{PO}_3^{2-}$), particularly preferably carboxylate ($-\text{COO}^-$);
- Sp = an alkylene group with 1 to 18 carbon atoms, an oxyalkylene group with 1 to 18 carbon atoms and 0 to 6 oxygen atoms or an arylene group with 6 to 14 carbon atoms, the spacer Sp being able to contain one or more, preferably 0 to 2 of the groups O, S, CO-O, O-CO, CO-NH, NH-CO, O-CO-NH, NH-CO-O and NH;

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particularly preferably, Sp is an alkylene group with 1 to 6, in particular 1 to 3 carbon atoms or is absent;

Z = an ethylenically unsaturated group, an epoxide, oxetane, vinyl ether, 1,3-dioxolane, spiroorthoester, particularly preferably a methacrylic and/or acrylic group;

a = 2 to 11;

b = 0 to 4.

The values of the indices c, d, e and f again correlate to the number and charge of the metal atoms. Preferably, they assume values such that the charge of the cluster is equalized. Typical values for c are in the case of the preferred clusters 1 to 11, in particular 2 to 5, for d and e 0 to 10 and in particular 0 to 8, for f 4 to 20 and in particular 6 to 15.

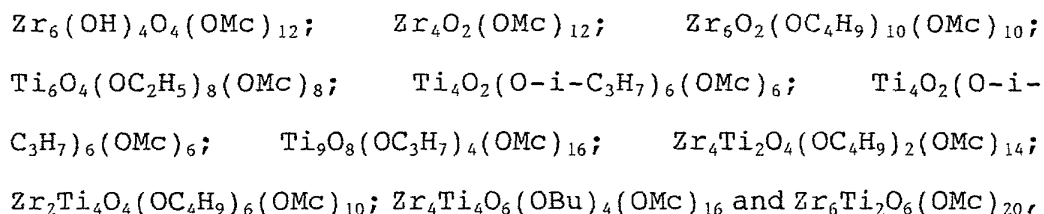
According to a particularly preferred version, $M^1 = M^2$. Clusters in which M^1 and M^2 are each zirconium are particularly preferred.

The polymerizable groups Z are preferably bound to the metal centres direct or by a short spacer via carboxylate groups.

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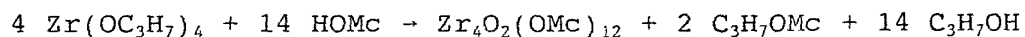
Particularly preferred ligands of the type (L-Sp-Z) are acrylate, methacrylate, oleate, allyl acetoacetate and acetoacetoxylethyl methacrylate.

Particularly preferred clusters are:



OMc in each case standing for a methacrylate group. Similarly preferred are the clusters which contain acrylate groups instead of the methacrylate groups.

The clusters according to formula (I) can be prepared by reacting metal alkoxides with suitable polymerizable ligands, optionally with the addition of water. For example, the reaction of zirconium(IV)-propoxide ($\text{Zr}(\text{O-C}_3\text{H}_7)_4$) with a quadruple molar excess of methacrylic acid (HOMc) produces clusters of the composition $\text{Zr}_4\text{O}_2(\text{OMc})_{12}$ (G. Kickelbick, U. Schubert, Chem. Ber./Recueil 130 (1997) 473):



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Moreover, suitable clusters can be prepared by the exchange of ligands for polymerizable ligands. For example, the reaction of titanium oxide clusters $Ti_aO_c(OOCR^\alpha)_e$ with unsaturated carboxylic acids ($HOOCR^\beta$) produces clusters of the composition $Ti_aO_c(OOCR^\alpha)_{e-u}(OOCR^\beta)_u$. Specifically, the reaction of the titanium carboxylate cluster $Ti_6O_4(OC_2H_5)_8(acetate)_8$ with methacrylic acid (HOMc) produces the cluster $Ti_6O_4(OC_2H_5)_8(acetate)_{8-u}(OMc)_u$.

Alternatively, suitable clusters can be obtained by the derivatization of inorganic clusters. For example, the reaction of $SiW_{11}O_{39}^{8-}$ with trichloro- or triethoxysilanes R^vSiQ_3 ($Q = Cl$ or OC_2H_5) in which R^v contains a polymerizable group produces polymerizable clusters of the composition $SiW_{11}O_{39}(OSi_2R_2)^{4-}$.

The clusters according to formula (I) represent substances of high reactivity which can be processed alone or preferably in combination with other polymerizable components by polymerization to form mechanically stable layers, moulded bodies and fillers. These are characterized by a very small proportion of monomers which can be dissolved out by solvents and a high stability even in humid conditions. The mechanical properties of the cured materials are not impaired by water storage.

For curing, an initiator for ionic or radical polymerization is preferably added to the polymerizable

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clusters or mixtures of the clusters with other polymerizable components. Depending on the type of initiator used, the polymerization can be initiated thermally, by UV or visible light. In addition, the mixtures can contain further additives, such as for example colorants (pigments or dyes), stabilizers, flavoring agents, microbicidal active ingredients, plasticizers and/or UV absorbers. The clusters according to formula (I) and their mixtures are suitable in particular for use as dental materials or for the preparation of dental materials. By dental materials are preferably meant adhesives, coating materials, cements and in particular filling materials.

The clusters according to formula (I) have only a low volatility because of their high molecular weight and can therefore largely be safely processed. Through the size and structure as well as the number of polymerizable groups of the clusters, the cross-linking density and thereby the mechanical properties such as E-modulus and strength and the swelling behaviour in organic solvents of the cured materials can be selectively set. Size and structure of the clusters as well as the number of polymerizable groups per metal atom can be monitored by variations in the synthesis parameters. The cluster size and structure are governed by the ratio of metal oxide to ligand in the educt mixture, but also by the nature of the radicals R in the alkoxides $M^1(OR)_n$ or $M^2(OR)_n$ used. Furthermore, the mechanical

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properties such as strength and flexibility can be influenced via the distance between the metal centres and polymerizable radicals, i.e. via the length of the spacer groups -Sp-.

In the case of the clusters according to formula (I), the polymerizable groups are fixed to a compact particulate cluster structure. The result of this is that, upon polymerization, rigid products with a high cross-linking density are obtained. The clusters represent three-dimensional molecules with a defined spatial structure and size and allow, upon co-polymerization with other components, an optimum cross-linking density to be set for the purpose in question. The structure of the clusters guarantees a complete incorporation of the clusters into the polymer network. It ensures a uniform environment for all the polymerizable organic ligands, so that these are practically equivalent as regards their reaction with organic co-monomers, which results in a uniform polymer structure developing around each ligand.

In addition, the abrasiveness or the optical properties such as for example the refractive index can be varied via the type and number of metal atoms.

Substances in which the clusters are soluble, i.e. liquid materials in particular, are preferred as further polymerizable components. Radically or ionically

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polymerizable mono- and polyfunctional compounds can primarily be considered here, in particular polymerizable organic monomers and silanes and polysiloxanes with polymerizable groups as well as mixtures of these compounds.

Ethylenically unsaturated organic monomers, in particular monofunctional or polyfunctional methacrylates which can be used alone or in mixtures are preferred as polymerizable organic monomers. Mono(meth)acrylates such as methyl, ethyl, butyl, benzyl, furfuryl, phenyl(meth)acrylate, isobutyl(meth)acrylate, cyclohexyl(meth)acrylate and polyfunctional (meth)acrylates such as tetraethylene glycol di(meth)acrylate, triethylene glycol di(meth)acrylate, diethylene glycol di(meth)acrylate, ethylene glycol di(meth)acrylate, polyethylene glycol di(meth)acrylate, butanediol di(meth)acrylate, hexanediol di(meth)acrylate, 1,10-decanediol di(meth)acrylate, 1,12-dodecanediol di(meth)acrylate, bisphenol-A di(meth)acrylate, trimethylolpropane tri(meth)acrylate, 2,2-bis-4-(3-methacryloxy-2-hydroxypropoxy)-phenylpropane (bis-GMA), pentaerythritol tetra(meth)acrylate as well as the reaction products from isocyanates, in particular di- and/or triisocyanates, and OH-group-containing (meth)acrylates can be considered as preferred examples of these compounds. Examples of these are the reaction products of 1 mol 2,2,4-trimethylhexamethylene diisocyanate with 2 mol 2-hydroxyethylene methacrylate (UDMA) or 2 mol hydroxypropyl

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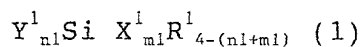
methacrylate as well as the reaction products of 2 mol glycerin dimethacrylate with 1 mol 2,2,4-trimethylhexamethylene diisocyanate, isophoron diisocyanate or $\alpha,\alpha,\alpha',\alpha'$ -tetramethyl-xylylene-m-diisocyanate. The use of polyfunctional (meth)acrylates is particularly preferred. By polyfunctional compounds are meant those with several polymerizable groups.

Further preferred polymerizable organic monomers are cationically polymerizable mono- or polyfunctional monomers such as 3,4-epoxycyclohexylmethyl-3,4-epoxycyclohexane carboxylate, bis-(3,4-epoxycyclohexylmethyl)adipate, vinylcyclohexene dioxide, 3-ethyl-3-hydroxymethyl oxetane, 1,10-decanediylbis(oxymethylene)bis(3-ethyloxetane) and 3,3-(4-xylylenedioxy)-bis-(methyl-3-ethyl-oxetane).

Compounds which have polymerizable groups, preferably (meth)acryl groups, or cationally polymerizable groups, preferably epoxide, oxetane, spiroorthoesters or vinyl ether groups, are particularly suitable as polymerizable silanes and polysiloxanes. Suitable silanes and polysiloxanes and their preparation are described in DE 41 33 494 C2, DE 44 16 857 C1, EP 1 022 012 A2 and US 6,096,903. Preferred silanes are listed below. Polysiloxanes based on these silanes are particularly preferred, the polysiloxanes being able to be present in the form of the homo- and co-condensates.

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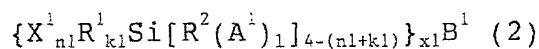
Silanes of the general formula (1) are preferred



in which the radicals X^1 , Y^1 and R^1 are the same or different and have the following meanings:

- R^1 = alkyl, alkenyl, aryl, alkylaryl or arylalkyl,
 X^1 = hydrogen, halogen, hydroxy, alkoxy, acyloxy, alkylcarbonyl, alkoxycarbonyl or NR^{δ}_2 with R^{δ} = hydrogen, alkyl or aryl,
 Y^1 = a substituent which contains a substituted or unsubstituted 1,4,6-trioxaspiro-[4,4]-nonane radical,
 n^1 = 1, 2 or 3,
 m^1 = 1, 2 or 3, with $n^1 + m^1 \leq 4$,

and silanes of the general formula (2),



in which radicals A^1 , R^1 , R^2 and X^1 are the same or different and have the following meanings:

- A^1 = O, S, PR^E , POR^E , $NHC(O)O$ or $NHC(O)ONR^E$,
 with R^E = hydrogen, alkyl or aryl,
 B^1 = a linear or branched organic radical which is

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derived from a compound $B^{1'}$ with at least one (for $l = 1$ and $A = \text{NHC(O)O}$ or NHC(O)NR^{ζ}) or at least two $\text{C}=\text{C}$ double bonds and 5 to 50 carbon atoms, with $R^{\zeta} = \text{hydrogen, alkyl or aryl,}$

- $R^1 = \text{alkyl, alkenyl, aryl, alkylaryl or arylalkyl,}$
 $R^2 = \text{alkylene, arylene or alkylene arylene,}$
 $X^1 = \text{hydrogen, halogen, hydroxy, alkoxy, acyloxy, alkylcarbonyl, alkoxy carbonyl or } \text{NR}^{\delta}_2 \text{ with } R^{\delta} = \text{hydrogen, alkyl or aryl,}$
 $n^1 = 1, 2 \text{ or } 3,$
 $k^1 = 0, 1 \text{ or } 2,$
 $l = 0 \text{ or } 1,$
 $X^1 = \text{an integer the maximum value of which corresponds to the number of double bonds in the compound } B^1 \text{ minus } 1 \text{ or is equal to the number of double bonds in the compound } B^1 \text{ when } l = 1 \text{ and } A \text{ stands for } \text{NHC(O)O} \text{ or } \text{NHC(O)ONR}^{\epsilon}.$

The silanes of the general formula (1) and (2) are hydrolyzable and polymerizable, the radicals X^1 being hydrolyzable and the radicals B^1 and Y^1 being polymerizable and in each case at least one radical B^1 , X^1 and Y^1 with the above-named meaning being present in the silanes of the general formula (1) and (2). Polysiloxanes based on silanes (1) and/or (2) are preferred polymerizable components.

The alkyl radicals of the compounds (1) and (2) are e.g. linear, branched or cyclic radicals with 1 to 20,

preferably 1 to 10 carbon atoms, and lower alkyl radicals with 1 to 6 carbon atoms are particularly preferred. Special examples are methyl, ethyl, N-propyl, i-propyl, n-butyl, s-butyl, t-butyl, i-butyl, n-pentyl, n-hexyl, cyclohexyl, 2-ethylhexyl, dodecyl and octadecyl.

The alkenyl radicals are e.g. linear, branched or cyclical radicals with 2 to 20, preferably 2 to 10 carbon atoms and lower alkenyl radicals with 2 to 6 carbon atoms such as e.g. vinyl, allyl or 2-butenyl are particularly preferred.

Preferred aryl radicals are phenyl, biphenyl and naphthyl.

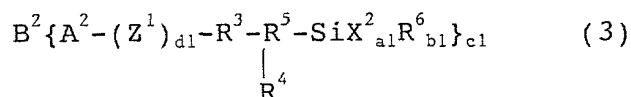
The alkoxy, acyloxy, alkylcarbonyl, alkoxycarbonyl and amino radicals are preferably derived from the above-named alkyl and aryl radicals. Special examples are methoxy, ethoxy, n- and i-propoxy, n-, i-, s- and t-butoxy, methylamino, ethylamino, dimethylamino, diethylamino, N-ethylamino, acetyloxy, propionyloxy, methylcarbonyl, ethylcarbonyl, methoxycarbonyl, ethoxycarbonyl, benzyl, 2-phenylethyl and tolyl.

The radicals named can optionally have one or more substituents, e.g. halogen, alkyl, hydroxyalkyl, alkoxy, aryl, aryloxy, alkylcarbonyl, alkoxycarbonyl, furfuryl, tetrahydrofurfuryl, amino, alkylamino, dialkylamino, trialkylammonium, amido, hydroxy, formyl, carboxy, mercapto, cyano, isocyanato, nitro, epoxy, SO_3H and PO_4H_2 .

Of the halogens, fluorine, chlorine and bromine are preferred.

The substituted or unsubstituted 1,4,6-trioxaspiro[4,4]-nonane groups are bound to the Si atom via alkylene or via alkenylene radicals which can be interrupted by ether or ester groups.

Further preferred are silanes according to the general formula (3) as well as polysiloxanes based on same



in which the radicals and indices have the following meanings:

- B^2 = a linear or branched organic radical with at least one C=C double bond and 4 to 50 carbon atoms;
- X^2 = hydrogen, halogen, hydroxy, alkoxy, acyloxy, alkylcarbonyl, alkoxycarbonyl or NR^7_2 ;
- R^6 = alkyl, alkenyl, aryl, alkylaryl or arylalkyl;
- R^5 = alkylene, arylene, arylenealkylene or alkylenearylene with in each case 0 to 10 carbon atoms, these radicals being able to be interrupted by oxygen and sulphur atoms or by amino groups;
- R^7 = hydrogen, alkyl or aryl;
- A^2 = O, S or NH for $d^1 = 1$ and $Z^1 = CO$

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and R^3 = alkylene, arylene or alkylenearylene with in each case 1 to 10 carbon atoms, these radicals being able to be interrupted by oxygen and sulphur atoms or by amino groups, and R^4 = COOH; or

A^2 = O, S or NH for $d^1 = 1$ and $Z^1 = CO$
and R^3 = alkylene, arylene or alkylenearylene with in each case 1 to 10 carbon atoms, these radicals being able to be interrupted by oxygen and sulphur atoms or by amino groups, and $R^4 = H$; or

A^2 = O, S, NH or COO for $d^1 = 1$ and $Z^1 = CHR^n$,
with R^n equal to H, alkyl, aryl or alkylaryl, and R^3 = alkylene, arylene or alkylenearylene with in each case 1 to 10 carbon atoms, these radicals being able to be interrupted by oxygen and sulphur atoms or by amino groups, and $R^4 = OH$; or

A^2 = O, S, NH or COO for $d^1 = 0$ and R^3 = alkylene, arylene or alkylenearylene with in each case 1 to 10 carbon atoms, these radicals being able to be interrupted by oxygen and sulphur atoms or by amino groups, and $R^4 = OH$; or

A^2 = S for $d^1 = 1$ and $Z^2 = CO$ and $R^3 = N$ and $R^4 = H$;

a^1 = 1, 2 or 3;

b^1 = 0, 1 or 2;

a^1+b^1 = 3;

c^1 = 1, 2, 3 or 4.

The silanes of the formula (3) are polymerizable via the radicals B^2 and hydrolyzable via the radicals X^2 .

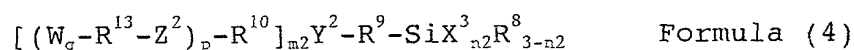
The optionally present alkyl, alkenyl, aryl, alkoxy, acyloxy, alkylcarbonyl, alkoxy carbonyl and amino radicals have the meanings defined for the formulae (1) and (2).

For $a^1 \geq 2$ or $b^1 = 2$, the radicals X^2 and R^7 can in each case have the same or a different meaning. The radical B^2 is

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derived from a substituted or unsubstituted compound $B^2(A^2H)_{c1}$ with at least one C=C double bond, such as e.g. vinyl, alkyl, acryl and/or methacryl groups and 4 to 50, preferably 6 to 30 carbon atoms. Preferably, B^2 is derived from a substituted or unsubstituted compound with two or more acrylate or methacrylate groups. Such compounds are also called (meth)acrylates. If the compound $B^2(A^2H)_{c1}$ is substituted, the substituents can be selected from the substituents named above. The group $-A^2H$ can be $-OH$, $-SH$, $-NH_2$ or $-COOH$ and c can assume values from 1 to 4.

Silanes according to formula (4) and polysiloxanes based on them are particularly preferred



in which

- X^3 stands for a halogen atom, a hydroxyl, alkoxy and/or acyloxy group;
- n^2 is equal to 1 to 3;
- R^8 stands for an alkyl, alkenyl, aryl, alkylaryl, arylalkyl group;
- R^9 stands for an alkylene group;
- R^{10} stands for a p-times substituted, linear, branched or cyclic, saturated or unsaturated, aromatic or aliphatic organic radical with 2 to 40 carbon atoms and optionally 1 to 6 heteroatoms;
- R^{13} stands for a q-times substituted linear, branched or cyclic organic radical with 1 to 20 carbon atoms or is absent;
- p is equal to 1 or 2;
- q is equal to 1 to 6;
- Y^2 stands for $-NR^{11}-$, N or $-(C=O)-NH-$;
- m^2 is equal to 2 for $Y^2 = N$ and equal to 1 for $Y = -NR^{11}-$ or $-(C=O)-NH-$;
- R^{11} stands for an alkyl or aryl group;

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Z^2 stands for O, S, $-(C=O)-O-$, $-(C=O)-NH-$, $-O-(C=O)-NH-$ or is absent;

W stands for $CH_2=CR^{12}-(C=O)-O-$; and

R^{12} stands for a hydrogen atom or an alkyl group.

Suitable heteroatoms are phosphorus and preferably oxygen.

In connection with formula (4), by alkyl, acyloxy, alkoxy, alkenyl groups and alkylene groups are meant radicals which preferably contain 1 to 25 carbon atoms, particularly preferably 1 to 10 carbon atoms and quite particularly preferably 1 to 4 carbon atoms and optionally bear one or more substitutes such as for example halogen atoms, nitro groups or alkyloxy radicals. By aryl is meant radicals, groups or substituents which preferably have 6 to 10 carbon atoms and can be substituted as stated above. The above definitions also apply to composite groups such as for example alkylaryl and arylalkyl groups. An alkylaryl group thus designates for example an aryl group as defined above which is substituted with an alkyl group as defined above.

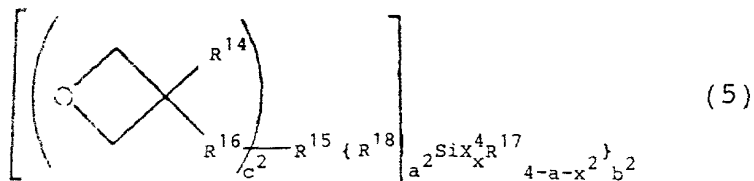
The alkyl, acyloxy, alkoxy, alkenyl groups and alkylene groups can be linear, branched or cyclical.

Preferred definitions, which can be selected independently of each other, for the individual variables of formula (4) are:

- X^3 = a methoxy and/or ethoxy group;
- n^2 = 2 or 3;
- R^8 = a C_1 to C_3 alkyl group, in particular a methyl group;
- R^9 = a C_1 to C_4 alkylene group;
- R^{10} = a p-times substituted linear, branched or cyclic, saturated or unsaturated, aromatic or aliphatic organic radical with 2 to 10 carbon atoms and optionally a hetero atom, preferably an

- oxygen atom, particularly preferably a C₁ to C₄ alkenylene radical or a monocyclic radical with 4 to 10, in particular 5 to 8 carbon atoms;
- R¹³ = a q-times substituted linear, branched or cyclical organic radical with 1 to 4 carbon atoms, particularly preferably a C₁ to C₃ alkylene radical;
- p = 1 or 2, in particular 1;
- q = 1 or 2;
- Y² = N or -(C=O)-NH-;
- Z² = -(C=O)-; and/or
- R¹² = a hydrogen atom or a methyl group.

Hydrolyzable and polymerizable oxetane silanes according to the general formula (5) and their stereoisomers as well as polysiloxanes based thereon are further preferred:



the variables R¹⁴, R¹⁵, R¹⁶, R¹⁷, R¹⁸, R¹⁹, R²⁰, X⁴, Y³, a², b², c², and x², unless otherwise stated, having the following meanings independently of each other:

- R¹⁴ = hydrogen or substituted or unsubstituted C₁ to C₁₀ alkyl;
- R¹⁵ = absent or substituted or unsubstituted C₁ to C₁₈ alkylene, C₆ to C₁₈ arylene, C₇ to C₁₈ alkylenearylene or arylenealkylene, these radicals being able to be interrupted by at least one group selected from ether, thioether, ester, carbonyl, amide and urethane group;
- R¹⁶ = absent or substituted or unsubstituted C₁ to C₁₈ alkylene, C₆ to C₁₈ arylene, C₇ to C₁₈ alkylenearylene or C₇ to C₁₈ arylenealkylene,

these radicals being able to be interrupted by at least one group selected from ether, thioether, ester, thioester, carbonyl, amide and urethane group or bear these in terminal position;

- R^{17} = absent or substituted or unsubstituted C_1 to C_{18} alkyl, C_2 to C_{18} alkenyl, C_6 to C_{18} aryl, C_7 to C_{18} alkylaryl or C_7 to C_{18} arylalkyl, these radicals being able to be interrupted by at least one group selected from ether, thioether, ester, carbonyl, amide and urethane group;
- R^{18} = absent or substituted or unsubstituted $-\text{CHR}^{20}-\text{CHR}^{20}-$, $-\text{CHR}^{20}-\text{CHR}^{20}-\text{S}-\text{R}^{19}-$, $-\text{S}-\text{R}^{19}-$, $-\text{Y}^3-\text{CO}-\text{NH}-\text{R}^{19}-$ or $-\text{CO}-\text{O}-\text{R}^{19}-$;
- R^{19} = substituted or unsubstituted C_1 to C_{18} alkylene, C_6 to C_{18} arylene, C_6 to C_{18} alkylenearylene or C_6 to C_{18} arylenealkylene, these radicals being able to be interrupted by at least one group selected from ether, thioether, ester, carbonyl, amide and urethane group;
- R^{20} = hydrogen or substituted or unsubstituted C_1 to C_{18} alkyl or C_6 to C_{10} aryl;
- X^4 = a hydrolyzable group, namely halogen, hydroxy, alkoxy or acyloxy;
- Y^3 = O or S;
- a^2 = 1, 2 or 3;
- b^2 = 1, 2 or 3;
- c^2 = 1 to 6; and
- x^2 = 1, 2 or 3;

and on condition that (i) $a^2+x^2 = 2, 3$ or 4 and (ii) a^2 and/or $b^2 = 1$.

However, the above formulae cover only such compounds which are compatible with the doctrine of valence.

Normally, the silanes according to formula (5) are present as stereoisomer mixtures and in particular as racemic compounds.

The ether, thioether, ester, thioester, carbonyl, amide and urethane groups possibly present in the case of the radicals of formula (5) are defined by the following formulae: -O-, -S-, -CO-O-, -O-CO-, -CO-S-, -S-CO-, -CS-O-, -O-CS-, -CO-, -CO-NH-, -NH-CO-, -O-CO-NH- and -NH-CO-O-.

The non-aromatic radicals or non-aromatic parts of the radicals which can be present in formula (5) can be linear, branched or cyclic.

In the silanes according to formula (5), any alkyl radicals present have preferably 1 to 8 and particularly preferably 1 to 4 carbon atoms. Special examples of possible alkyl radicals are methyl, ethyl, n- and iso-propyl, sec.- and tert.-butyl, n-pentyl, cyclohexyl, 2-ethylhexyl and octadecyl.

In the silanes according to formula (5), any alkenyl radicals present have preferably 2 to 10 and particularly preferably 3 to 6 carbon atoms. Special examples of possible alkenyl radicals are vinyl, allyl- and iso-butenyl.

Preferred examples of possible aryl radicals of the formula (5) are phenyl, biphenyl and naphthyl. Alkoxy radicals have preferably 1 to 6 carbon atoms. Special examples of possible alkoxy radicals are methoxy, ethoxy, n-propoxy, iso-propoxy and tert.-butoxy. Acyloxy radicals have preferably 2 to 5 carbon atoms. Special examples are acetyloxy and propionyloxy.

Preferred alkylene radicals of formula (5) are derived from the above preferred alkyl radicals, and preferred arylene radicals are derived from the above preferred aryl radicals. Preferred radicals which consist of a combination of a non-aromatic and aromatic part are derived from the

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above preferred alkyl and aryl radicals. Special examples of this are benzyl, 2-phenylethyl and tolyl.

The named substituted R radicals of formula (5) bear one or more single substituents. Examples of these substituents are methyl, ethyl, phenyl, benzyl, hydroxymethyl, hydroxyethyl, methoxy, ethoxy, chlorine, bromine, hydroxy, mercapto, isocyanato, vinyloxy, acryloxy, methacryloxy, allyl, styryl, epoxy, carboxyl, SO_3H , PO_3H_2 or PO_4H_2 .

For a^2 , b^2 , c^2 or $x^2 \geq 2$, the radicals X^4 as well as the individual R radicals can in each case have the same or a different meaning.

In addition, preferred definitions exist for the variables of formula (5) set out above which, unless otherwise stated, can be selected independently of each other and are as follows:

- R^{14} = hydrogen or C_1 to C_5 alkyl;
- R^{15} = C_1 to C_8 alkylene, these radicals being able to be interrupted by at least one group selected from ether, thioether, ester and urethane group;
- R^{16} = absent or C_1 to C_8 alkylene, these radicals being able to be interrupted by at least one group selected from ether, thioether, ester, thioester, carbonyl, amide and urethane group or bear these in terminal position;
- R^{17} = absent or methyl, ethyl or phenyl;
- R^{18} = absent or $-\text{CHR}^{20}-\text{CHR}^{20}-$, $-\text{S}-\text{R}^{19}-$, $-\text{Y}-\text{CO}-\text{NH}-\text{R}^{19}-$ or $-\text{CO}-\text{O}-\text{R}^{19}-$;
- R^{19} = C_1 to C_8 alkylene, these radicals being able to be interrupted by at least one group selected from ether, thioether, ester, carbonyl, amide and urethane group;
- R^{20} = hydrogen or C_1 to C_5 alkyl;
- X^4 = methoxy, ethoxy or chlorine;

$$\begin{aligned}
 Y^3 &= 0 \text{ or } S; \\
 a^2 &= 1; \\
 b^2 &= 1; \\
 c^2 &= 1 \text{ to } 6; \\
 x^2 &= 2 \text{ or } 3; \text{ and/or} \\
 a^2+x^2 &= 3.
 \end{aligned}$$

The individual R radicals can in turn bear single substituents.

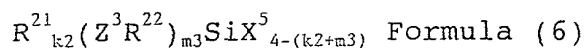
Preferred compounds according to formula (5) are accordingly those for which at least one of the variables of formula (5) meets the preferred definition described above.

Furthermore, oxetane silanes of formula (5) are preferred for which the indices a^2 , b^2 and/or c^2 have the value 1.

The silanes (5) are polymerizable via the oxetane groups and hydrolyzable via the radicals X^4 .

The above-named silanes can be processed, either alone or together with other hydrolytically condensable compounds of silicon, aluminium, zirconium, titanium, boron, tin, vanadium and/or phosphorus to form polysiloxanes. These additional compounds can be used either per se or already in pre-condensed form.

Preferred further hydrolytically compounds of silicon are silanes of the general formula (6)



in which

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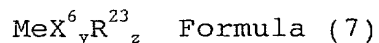
- R^{21} stands for a C_1 to C_8 alkyl, C_2 to C_{12} alkenyl or C_6 to C_{14} aryl group;
 R^{22} stands for a C_1 to C_8 alkylene, C_2 to C_{12} alkenylene or C_6 to C_{14} arylene group;
 X^5 stands for a hydrogen or halogen atom or a C_1 to C_8 alkoxy group;
 Z^3 stands for a glycidyl, acryl, methacryl, vinyl, allyl or vinylether group;
 k^2 is equal to 0, 1, 2 or 3;
 m^3 is equal to 0, 1, 2 or 3; and
 k^2+m^3 is equal to 0, 1, 2 or 3.

Preferred definitions, which can be selected independently of each other, for the individual variables are:

- R^{21} = a C_1 to C_3 alkyl, C_2 to C_5 alkenyl or a phenyl group;
 R^{22} = a C_1 to C_3 alkylene, C_2 to C_5 alkenylene or a phenylene group;
 X^5 = a halogen atom, a methoxy or ethoxy group;
 Z^3 = an acryl or methacryl group;
 k^2 = 0 and 1;
 m^3 = 0 and 1;
 k^2+m^3 = 0, 1 or 2.

Such silanes are described for example in DE 34 07 087 A1.

Preferred zirconium, titanium compounds for the co-condensation with the named silanes are those according to formula (7)



in which

Me stands for Zr or Ti;

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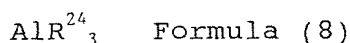
- R^{23} stands for a hydrogen atom, a substituted or unsubstituted C_1 to C_{12} alkyl, C_1 to C_{15} alkylaryl or C_6 to C_{14} aryl group;
 X^6 stands for a halogen atom, a hydroxyl or C_1 to C_8 alkoxy group;
 Y is equal to 1 to 4;
 z is equal to 0 to 3.

Preferred definitions, which can be selected independently of each other, for the individual variables are:

- R^{23} = a C_1 to C_5 alkyl or a phenyl group;
 X^6 = a halogen atom, a methoxy, ethoxy or propoxy group;
 Y = 4;
 z = 0 or 1, in particular 0.

Particularly preferred zirconium and titanium compounds are $ZrCl_4$, $Zr(OC_2H_5)_4$, $Zr(OC_3H_7)_4$, $Zr(OC_4H_9)_4$, $ZrOCl_2$, $TiCl_4$, $Ti(OC_2H_5)_4$, $Ti(OC_3H_7)_4$ and $Ti(OC_4H_9)_4$.

Preferred aluminium compounds are those according to formula (8)



in which

- R^{24} stands for a halogen atom, a hydroxyl or C_1 to C_8 alkoxy group, preferably for a halogen atom or a C_1 to C_5 alkoxy group.

Particularly preferred aluminium compounds are $Al(OCH_3)_3$, $Al(OC_2H_5)_3$, $Al(OC_3H_7)_3$, $Al(OC_4H_9)_3$ and $AlCl_3$.

In addition, boron trihalides, tin tetrahalides, tin tetraalkoxides and/or vanadyl compounds are suitable for co-condensation with the above-named silanes.

The curing of the materials takes place, depending on the initiator used, by thermal, photochemical or redox-induced polymerization.

Peroxides, in particular dibenzoyl peroxide, dilauroyl peroxide, tert.-butyl peroctoate and tert.-butyl perbenzoate are preferred as initiators for the hot-curing systems. In addition, azobisisobutyroethylester, 2,2'-azobisisobutyronitrile (AIBN), benzopinacol and 2,2'-dialkylbenzopinacols are suitable.

Radical-supplying systems, for example benzoyl peroxide, lauroyl peroxide or preferably dibenzoyl peroxide, together with amines such as N,N-dimethyl-p-toluidine, N,N-dihydroxyethyl-p-toluidine, N,N-dimethyl-sym.-xylidine or other structurally-related amines are used as initiators for cold polymerization. Amine and peroxide are usually distributed over two different components of the dental material. Upon mixing of the amine-containing base paste with the peroxide-containing initiator paste, the radical polymerization is initiated by the reaction of amine and peroxide.

Benzophenone and its derivatives as well as benzoin and its derivatives can be used for example as initiators for photopolymerization. Further preferred photoinitiators are the α -diketones such as 9,10-phenanthrenquinone, diacetyl, furil, anisil, 4,4'-dichlorobenzil and 4,4'-dialkoxybenzil. Camphorquinone and 2,2-methoxy-2-phenyl-acetophenone and in particular α -diketones in combination with amines as reduction agents are particularly preferably used. Preferred amines are 4-(N,N-dimethylamino)-benzoic acid ester, N,N-dimethylaminoethyl methacrylate, N,N-dimethyl-

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sym.-xylidine and triethanolamine. In addition, acyl phosphines such as e.g. 2,4,6-trimethylbenzoyldiphenyl- or bis-(2,6-dichlorobenzoyl)-4-N-propylphenylphosphinic oxide are also particularly suitable as photoinitiators.

For curing cationically polymerizable systems, diaryl-iodonium or triarylsulfonium salts such as e.g. triphenylsulfonium hexafluorophosphate or hexafluoro-antimonate are particularly suitable as well as the photoinitiator systems described in WO 96/13538 and WO 98/47047.

Furthermore, the mixtures can be filled with organic or inorganic particles or fibres to improve the mechanical properties. In particular, amorphous, spherical materials based on mixed oxides of SiO_2 , ZrO_2 and/or TiO_2 with a mean average particle size of 0.005 to 2.0 μm , preferably from 0.1 to 1 μm , as disclosed for example in DE-PS 32 47 800, microfine fillers such as pyrogenic silicic acid or precipitation silicic acid as well as macro- or mini-fillers, such as quartz, glass ceramic or glass powder with an average particle size of 0.01 to 20 μm , preferably 0.5 to 5 μm as well as x-ray-opaque fillers such as ytterbium fluoride, are suitable as filler components. By mini-fillers are meant fillers with a particle size of 0.5 to 1.5 μm , and by macro-fillers fillers with a particle size of 10 to 20 μm .

Preferred compositions according to the invention contain, relative to their overall mass:

- (a) 5 to 90% wt.-%, in particular 5 to 40 wt.-%, quite particularly preferably 10 to 20 wt.-% of one or more clusters according to formula (I),
- (b) 10 to 90 wt.-%, in particular 10 to 80 wt.-% of one or more further polymerizable components,

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- (c) 0.1 to 5.0 wt.-%, in particular 0.2 to 2.0 polymerization initiator,
- and
- (d) 0 to 90 wt.-%, in particular 0 to 80 wt.-% filler.

The above composition can be further optimized in accordance with the desired use. Thus, a material which is particularly suitable as dental filling material preferably contains, in each case relative to the overall mass of the material:

- (a) 5 to 20% wt.-% of one or more clusters according to formula (I),
- (b) 0 to 20 wt.-% of one or more further polymerizable components,
- (c) 0.2 to 2.0 wt.-% 2.0 polymerization initiator,
- and
- (d) 5 to 80 wt.-% filler.

A dental material which is particularly suitable as dental cement preferably contains, in each case relative to the overall mass of the material:

- (a) 5 to 30% wt.-% of one or more clusters according to formula (I),
- (b) 0 to 30 wt.-% of one or more further polymerizable components,
- (c) 0.2 to 2.0 wt.-% 2.0 polymerization initiator,
- and
- (d) 5 to 60 wt.-% filler.

A dental material which is particularly suitable as dental coating material preferably contains, in each case relative to the overall mass of the material:

- (a) 5 to 40% wt.-% of one or more clusters according to formula (I),

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- (b) 5 to 80 wt.-% of one or more further polymerizable components,
- (c) 0.2 to 2.0 wt.-% 2.0 polymerization initiator, and
- (d) 0 to 40 wt.-% filler.

Quite particularly preferred are materials which contain, as further polymerizable component (b), 10 to 90 wt.-% polysiloxane and 0 to 40 wt.-% polymerizable organic monomers, in each case relative to the overall mass of the dental material.

These compositions are particularly suitable as dental materials, quite particularly as adhesives, for example for inlays, coating materials, cements and in particular filling materials. In general, the compositions are particularly suitable for those uses in which the curing of the material takes place in the mouth cavity.

After polymerization, the dental materials according to the invention have only a minimal content of unpolymerized constituents which can be dissolved out with aqueous or alcoholic solvents, which represents a significant improvement vis-à-vis conventional dental materials, as toxic side effects caused by monomeric constituents are suppressed.

According to the invention, clusters of a defined size and structure, i.e. pure, defined compounds of a known stoichiometry, are used for the preparation of dental materials, particularly preferably clusters with monodispersed mass distribution. In this way, the material properties of the dental materials, such as for example E-modulus, strength, hardness and abrasivity, can be set and improved in a controlled manner. Dental materials which contain 1 to 2 different clusters are preferred.

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In the following, the invention is explained in more detail using examples.

Example 1:

Synthesis of the oxozirconium methacrylate cluster of composition $Zr_4O_2(OMc)_{12}$

2.04 g (24 mmol) methacrylic acid were added to 1.73 g (3.6 mmol) of an 80% solution of zirconium butylate ($Zr(OC_4H_9)_4$) in n-butanol. The reaction mixture was left to stand for a day at room temperature and the formed precipitate filtered off accompanied by the exclusion of moisture. 1.09 g (86% yield) of colourless cubic crystals resulted, which are soluble in chloroform, ethanol or toluene.

Example 2:

Synthesis of matrix substances based on silicic acid polycondensate

A) Hydrolytic condensation of bis[(methacryloyloxy)propoxycarbonylethyl]-[3-(triethoxysilylpropyl)]amine:

16.1 g (26 mmol) bis[(methacryloyloxy)propoxy-carbonylethyl]-[3-(triethoxysilylpropyl)]amine which is obtainable by Michael addition of 3-aminopropyltriethoxysilane to 2-(acryloyloxyethyl)-propyl methacrylate (cf. EP 1 022 012) were dissolved in 37.5 ml anhydrous ethanol and hydrolytically condensed accompanied by the addition of 2.81 g of an aqueous 0.1 N ammonium fluoride solution. After 24 h stirring at room temperature, the volatile components were removed in vacuum and approx. 12 g of a relatively low-viscosity resin (SG-1) with a viscosity of $\eta = \text{ca. } 8 \text{ Pas}$ (23°C) remained. This and all other viscosity data, unless otherwise stated, involves the rotation viscosity measured with a rotation rheometer with a

parallel-plate measuring system, CV = 120 (model CVO 120 of the company Bohlin).

B) Hydrolytic condensation of (3-triethoxysilylpropylaminocarbonyl)butyric acid-(1,3(2)-bismethacryloyloxypropyl)ester:

10.9 g (20 mmol) (3-triethoxysilylpropylamido)butyric acid-(1,3-(2)-bismethacryloyloxypropyl)ester, which was obtained by amidation from 3-aminopropyltriethoxysilane with the adduct from glycerin dimethacrylate and glutaric acid anhydride (cf. EP 1 022 012), were dissolved in 98.2 mol anhydrous ethyl acetate and hydrolytically condensed accompanied by the addition of 1.08 g 0.5 N hydrochloric acid. After 30 minutes' stirring at 40°C, the volatile components were removed in vacuum. The resin obtained was then silylated after dissolving in a mixture of 35 g tert.-butylmethyl-ether, 12 g THF and 1.45 g (12 mmol) 2,4,6-trimethylpyridine by the dropwise addition of 1.96 g (18 mmol) trimethylchlorosilane. After stirring overnight at room temperature, the reaction mixture was washed with diluted hydrochloric acid and saturated NaCl solution and then dried over anhydrous sodium sulphate. After the evaporation of the solvent in vacuum, ca. 6 g of a viscous resin (SG-2) with a viscosity of η = ca. 75 Pas (23°C) remained.

Example 3:

Preparation of dental materials based on clusters according to example 1

Various materials were prepared starting from the cluster $Zr_4O_2(OMc)_{12}$ from example 1 and the matrix substances ST-1 and SG-2. The clusters were mixed with the matrix substances as 10% solution in ethanol and the solvent evaporated off in vacuum after the addition of the

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initiator components. The compositions (mass %) of the thus-prepared unfilled materials M-1 to M-5 are listed in Table 1. To determine the mechanical properties, testpieces with the dimensions 25 x 2 x 2 mm were prepared from the compositions and cured by illumination with light of a wavelength of 390 to 500 nm (6 minutes). For this purpose, a dental radiation source of the Spectramat type from Vivadent was used. The bending strength (BS) and the bending E-modulus (BEM) were determined according to the ISO standard 4049 (2000), the testpieces having been previously stored in water at 37°C for 24 h. In addition, BS and BEM values were also measured for samples which were stored dry for 24 h at 37°C.

Table 1: Composition (mass %) of the unfilled materials M-1 to M-5

	M-1*)	M-2	M-3*)	M-4	M-5
SG-1	98.7	88.7	-	-	-
SG-2	-	-	98.7	88.7	78.7
Zr-Cluster from Example 1	-	10.0	-	10.0	20
Photoinitiator ^{a)}	1.3	1.3	1.3	1.3	1.3

*) Comparison example without clusters

a) A mixture of 0.3% camphorquinone, 0.6% 4-(N,N-dimethylamino)-benzoic acid ethyl ester and 0.4% acryl phosphinic oxide (Lucerin TPO, BASF) was used as photoinitiator

Table 2: Bending strength (BS) and Bending E-modulus (BEM) of materials M-1 to M-5

	M-1*)	M-2	M-3*)	M-4	M-5
Dry BF (MPa)	46	47	48	59	70
H ₂ O storage BS (MPa)	31	52	36	60	60
Dry BEM (MPa)	1230	1900	1820	2100	2400
H ₂ O storage BEM (MPa)	1000	1920	1750	2270	2600

*) Comparison example without clusters

To prepare the composite pastes C-1 to C-5, the unfilled materials M-1 to M-5 were mixed with the quantities of filler given in Table 3. Silanized pyrogenic silicic acid with an average primary particle size of 40 nm and a BET surface of 50 m²/g (silanized Aerosil OX-50, Degussa), ytterbium trifluoride with an average particle size of 5 µm and a BET surface of < 7.5 m²/g (YbF₃, Auer Remy), silanized SiO₂-ZrO₂ mixed oxide with a primary particle size of 130 to 230 nm (Sphärosil, Tokoyma Soda) and silanized barium silicate glass (Ba-Si glass) with an average particle size of 1.2 µm were used as fillers. The filler components are incorporated by means of a capsule vibrator.

The bending strength and the bending E-modulus were then measured, in each case after 24-hour storage in water or in the dry. The results are summarized in Table 4.

Table 3: Composition of the composite pastes C-1 to C-5
(values in mass %)

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	K-1*)	K-2	K-3*)	K-4	K-5
Unfilled material	25.0 (M-1)	25.0 (M-2)	25.0 (M-3)	25.0 (M-4)	25.0 (M-5)
Aerosil OX-50	1.0	1.0	1.0	1.0	1.0
YbF ₃	15.0	15.0	15.0	15.0	15.0
Sphärosil	15.0	15.0	15.0	15.0	15.0
Ba-Si glass	44.0	44.0	44.0	44.0	44.0

*) Comparison example without clusters

Table 4: Bending strength (BS) and bending E-modulus (BEM) of the composites C-1 to C-5

	K-1*)	K-2	K-3*)	K-4	K-5
Dry BS (MPa)	94	96	89	101	103
H ₂ O storage BS (MPa)	68	100	89	110	113
Dry BEM (MPa)	6400	8900	8150	9100	9840
H ₂ O storage BEM (MPa)	5500	9300	7160	9750	10900

*) Comparison without clusters

The results show (Tables 2 and 4) that the addition of clusters of the composition $Zr_4O_2(OMc)_{12}$ in each case leads to an improvement in strength and to an increase in E-modulus of the materials. In addition, in the case of the cluster-containing materials, an increase in the E-modulus after water storage can be observed, whereas the E-modulus

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decreases in the case of the non-modified samples M-1/C-1 and M-3/C-3 after water storage.

Samples of the cured composites C-2 and C-4 were crushed and the fragments dispersed in ethanol at 37°C. After 72 h, the solid constituents were filtered off and the filtrate concentrated to dryness. Almost no residue resulted, which indicates a complete incorporation of the polymerizable components into the polymer network of the composite matrix.

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